SPECIAL REPORT ON SYSTEM NO. 2N

On 31 May 1955, this contractor submitted a technical exhibit outlining the proposed development of a combination navigation and communication system. That system was based upon performing ranging on the aircraft by measuring the round-trip time of propagation of a signal from a ground station to aircraft and return. One-half of the measured time interval, corrected for time delays experienced by the signal in the several circuits through which it was transmitted, would provide information with respect to the true radio path length between ground and aircraft. Measurement of the vertical angle of arrival of signals received on the ground from the aircraft would be employed to correct the radio path length to a true ground path length value, thereby giving true range to the aircraft. Bearing information was to have been secured by r-f phase comparison of signals received by three antennas located at the ground station.

Instrumentation for verifying the basic principles underlying operation of the system proposed was completed late during the month of June, and a series of experimental transmissions was conducted between [redacted] 25X1A
25X1A [redacted] and [redacted] during the period extending from 25X1A
5 July 1955 to 8 July 1955, inclusive. These tests established that the phase stability of signals propagated via the ionosphere was inadequate to permit measurement of vertical angles of arrival and azimuth angles with the precision necessary for satisfactory navigation, and a search was immediately instituted for other bases upon which the development of the navigation system could proceed.

Because of the comparatively high stability of low-frequency signal propagation, attention was directed to several techniques based upon the use of low-frequency radiation. Shortly after this approach was taken, however, engineers of the contracting agency pointed out that the establishment of new low-frequency transmitters within the general areas in which operations were to be conducted would prove to be extremely difficult, if not impossible, under some conditions. Accordingly, effort was directed toward the development of a system which would permit utilization of existing high-power, low-frequency broadcast stations, in the regions for which operations were planned, and a review of international assignments in the low-frequency band revealed that some 15 or more such stations were in operation in the region west of the Urals. The power of these transmitters ranged, in most cases, between 100 kw and 1000 kw - values which were obviously far in excess of any which could be provided by special transmitters developed and placed in operation for this program. It was noted additionally that these stations could well be expected to be equipped with antennas exhibiting far greater efficiency than any that we could hope to erect. Accordingly, it seemed profitable to investigate the feasibility of utilizing radiation from these sources as the basis for navigation system development.

A method of employing the integrated value of the Doppler effect created in the apparent carrier frequency of such stations resulting from motion of the airplane was devised and subjected to analysis. In theory, at least, simultaneous measurement of Doppler frequency on four high-power, low-frequency ground stations should permit an accurate determination of the position of an airplane, and such additional information as might be required to compute an accurate track. It soon became apparent, however, that solution of the four simultaneous equations necessary to secure a navigational fix represented a very complex undertaking; to this day it has not been determined whether an adequate solution could be secured without the aid of a high-speed digital computer. Simultaneously with the conduct of this work, calculations were made of field intensity produced by several of the high-powered broadcast transmitters. The data obtained in this manner was discouraging; it indicated that extreme difficulty would be encountered in attempting to secure cycle counts on the low-frequency sources for the extended periods required if inaccuracies in navigation resulting from the counting process were not to be excessive at ranges in excess of 1500 miles from the ground sources.

Further complications in this program were injected by realization of the fact that a number of the high-powered broadcast sources were under Soviet control and, in consequence, could well have been incorporated in the Soviet equivalent of our Conelrad system. Conelrad operations of these stations would render them utterly useless to us as tools in our navigational system. It was learned, also, that essentially none of the high-power European broadcast stations operate on an around-the-clock basis and that, in consequence, there could be no assurance on our part that radiation sources favorable to our needs would be operating throughout the period required.

Finally, and comparatively recently, the contracting agency made available to this contractor two ASTIA documents which contained information vitally affecting our recent decisions. The first of these was an evaluation report on the performance characteristics of the Navarho system, which was prepared by the Rome Air Development Center in July, 1955. Figure 17 of that report presents the results of measurements made on so-called breadboard versions of the Navarho system after various elements of that system had been under development for the better part of ten years. Reference to that figure indicates that at 1000 nautical miles range, the fix error would be 40 miles or less for 90% of the time when measurements were made over land; at 1600 nautical miles range, the fix error, for 90% of the time, would be 80 miles or less. Undoubtedly a large fraction of the error indicated is instrumentation error; nevertheless, it is probable that between one-third and one-half the error indicated could be attributed to uncertainties in propagation. Such performance tends to give little reassurance that adequate low-frequency navigation could be achieved over distances of the order of 3000 to 4000 miles, as may be required in the present application.

In summary, then, although an approach to solution of the navigation problem based upon the use of low-frequency transmission appeared to be desirable from several points of view, the following factors caused grave concern relative to the degree of success that might be anticipated. Briefly, the factors were:

1. Attenuation of the low-frequency signals propagated over land was far greater than had been anticipated originally.

2. There was a possibility of Soviet Conelrad operation.

3. The contemplated system was deficient in the sense that we had no control of the periods of low-frequency station operation; information at hand indicated strongly that sustained operation over 18 to 20 hours of the day was highly improbable.

4. Experimental results of Navarho operation did not indicate the high degree of propagation stability that had been assumed previously.

5. It is known that there are comparatively few medium-powered low-frequency broadcast stations in operation in the Far East, and that no high-power stations of this kind exist there.

6. No medium-power or high-power, low-frequency broadcast stations are in existence in the United States. In consequence, it would be impossible to conduct test flights of the systems proposed in this country, and there could be no assurance that operation of the equipment developed to utilize the principle of integrated Doppler navigation would perform satisfactorily until test flights had been made overseas.

These factors dictated strongly against a continuation of the low-frequency system development, and some effort was being redirected to consideration of new approaches to a solution of the navigation problem based upon the utilization of high-frequency transmissions. About this time a report was received summarizing the results of certain experiments conducted at
25X1A the [redacted] in the field of short-base direction finding systems. The information contained in this report presented essentially a verification of certain concepts which had occurred to members of this contractor's staff shortly after the conclusion of our first propagation tests from [redacted] 25X1A
25X1A [redacted] In effect, the [redacted] data verified the theory that integration of bearing data over a period of several minutes could reduce the fluctuations in apparent bearing angle to a value sufficiently small to permit effective use of high-frequency bearing data for navigational purposes. If a correction is added to the data contained in the [redacted] report to account for the effects of aircraft motion, it seems most probable that bearing data accurate to within $\pm 0.5^{\circ}$ can be secured by signal integration over periods in the neighborhood of one minute. The support provided by the [redacted] data to the concepts which 25X1A

25X1A

had grown from the [redacted] propagation tests was sufficient, when added to the uncertainties that had grown with respect to low-frequency operation, to force a decision to return to development of a high-frequency system. Thus, after some months of effort, this contractor is in the position of having completed a circuit which leads essentially to little more than an important modification of the original navigation system approach that was proposed in May of this year. The new ingredient that has been thrown into the system presently under development is the concept that integration of angle-of-arrival information can so reduce the fluctuations in that data as to render it of sufficient accuracy for operational use.

A brief description of the navigation system now under forced-draft development is probably in order. In some respects, the system operates in a manner inverse to that proposed originally. Three simple vertical radiators on the ground, designated for convenience as A, B, and C, radiate signals which are utilized to provide navigation data to the aircraft. These antennas may be arranged in the form of an equilateral triangle or in such other configuration as site requirements dictate. In principle, a signal of reference phase is transmitted in the form of a pulse train from Antenna A. A short time thereafter, Antennas A and B are excited simultaneously in predetermined phase relationship, and a short time after that, Antennas A and C are excited simultaneously in another predetermined phase relationship. If the phase of the signal received on the aircraft from Antenna A alone can be compared precisely with the phase of the signals received from A and B, and from A and C, the phase data so obtained can be employed in conjunction with simple range data obtained by high-frequency transponder action to provide a navigational fix free of error resulting from uncertainty in ionospheric layer height. Further, if phase comparison between the signals originating from Antenna A alone and those originating from the pairs A and B and then from A and C can be integrated for a period of one or two minutes, fluctuations in the data can be reduced statistically to a value acceptably small for the purpose at hand.

Unfortunately, the techniques for effecting a phase comparison between signals arriving at two different times are most difficult, and in consequence, direct measurement of the phase angles with the accuracies required is highly improbable of accomplishment at this time. However, it will be recognized that the amplitude of the signal produced at the aircraft by simultaneous excitation of antennas A and B is related to the amplitude of the signal produced by excitation of Antenna A alone in a manner critically dependent upon the phase relationship which it is desired to determine; a similar situation exists for the signals arising from simultaneous excitation of Antennas A and C and those from Antenna A alone. Now it is possible to measure amplitudes with as much precision as can be achieved in phase measurements directly. More importantly, amplitude information can be stored readily for extended periods of time; it is equally true that it can be integrated over extended periods of time without resorting to techniques that have not already been developed. Therefore, the problem of navigation in the present approach reduces to one of first measuring precisely the amplitude of the signal from Antenna A, then measuring with equal precision the amplitude of the signal from Antennas A and B, and finally performing a similar measurement of the amplitude caused by excitation of Antennas A and C. If such amplitude measurements are made repeatedly at rates in the neighborhood of 30 times per second for a total period of about one minute, and the information so derived is stored and integrated throughout that period, the fluctuations observed on individual measurements will have been reduced by the process of integration to a point where fluctuation errors are no longer of primary importance. The integrated amplitude data may be converted at will to equivalent bearing information by a relatively simple analytical process.

It is proposed, in practice, to excite the three vertical radiators periodically and in time sequence for a period of one minute. During this interval, the amplitudes of the signals received on the aircraft will be evaluated precisely and stored in two digital integrators. Near the conclusion of this period, special high-frequency ranging signals will be transmitted from the ground, and these, too, will be integrated, but only for a period of approximately five seconds. At the conclusion of the one-minute period, the aircraft will automatically transpond the range signals and immediately thereafter will read out of the counters employed for digital storage of the integrated bearing information the data to be transmitted to ground. The three pieces of information thus relayed to ground - namely, the range data and the two integrated pieces of bearing data - will be processed to determine a fix, and the position of the aircraft will be relayed over the communication link to the airplane for display to the pilot.

The navigation system will utilize the transmission of pulses approximately 125 microseconds in length. A train of such pulses, employing bi-phase coding, will be transmitted from each of the ground antennas to permit some signal integration on the airplane to enhance signal-to-noise ratios.

At least two general sources of error exist in this type of navigation. The first of these is that class of error which may be termed "siting" error; it includes those errors resulting from uncertainty in antenna performance brought about by nonuniformity in ground conductivity and dielectric constant in the general neighborhood of the antenna array, and due to ground slope and similar physical factors. The second class of errors results from deviations in signal propagation path from the great circle joining the ground transmitter and the aircraft. Such deviations will most commonly result from ionospheric tilt; they will be most pronounced during the sunrise and sunset periods, and comparatively unimportant at other times.

Errors falling in the first class can be minimized, if not eliminated, by suitable calibration of the ground system. Errors of the second class are more difficult to cope with, and will generally be revealed most directly by securing fixes on the airplane from two well-separated ground stations.

It may be noted that when two ground stations are employed to secure independent sets of range and bearing data, sufficient information exists to permit fixed determination from the two values of range data alone, from the two values of bearing data alone, or from independent use of the range and bearing data secured at each ground station. Theoretically, the four fixes so obtained will superimpose exactly if the data is accurate; failure for such superposition to occur will be indicative immediately of error in one or more of the fixes. The magnitude and nature of that error can be employed to secure a second-approximation correction to the fix, thereby improving the over-all performance of the navigation system.

From the theoretical viewpoint, the system now under development has an inherent capability of meeting the navigational requirements of this project with more than acceptable accuracy. The system has the further advantage that all of the elements involved are under our control, thus rendering us quite independent of radiation sources external to the project. With moderately favorable signal propagation, it has been calculated that useful performance of the navigation system should be secured to ranges approximating 4000 miles, although lack of precise information concerning certain features of ionospheric propagation renders it difficult to estimate probable navigational error at extreme range. The present approach makes it possible to receive all signals required from the aircraft on high-gain rhombic antennas, thus minimizing to the greatest extent possible the need for unusually high radiated power from the airplane. For most conditions of operation, 3 kw to 4 kw of radiated ground power should prove adequate. In those cases where higher power is required, the addition of power amplifier equipment will, in all likelihood, prove to be feasible.

No other approach is known to the solution of the navigation problem, that would appear to offer so great a probability of success as the one presently being followed. A more detailed report providing block diagrams and other engineering data for both the communication and navigation system is now in process of preparation.

It would be most desirable, of course, to secure verification of some of the principles underlying this development prior to the end of this year. Every effort is being made to complete the construction of flyable hardware to permit acquisition of such information. Unfortunately, useful data concerning the performance of the system proposed cannot be obtained without instrumentation essentially so complete as to constitute a working communication and navigation system. For this reason, a complete checkout of all elements of the C and N system will be secured when the first navigation system tests are undertaken. Plans are presently being formulated for the establishment of ground-base facilities on land recently acquired by this contractor at a location which is but a few miles removed from the present plant site.

Design of the antenna system to be erected for complete tests of the C and N system is under way. It is expected that this design activity will be completed within a few weeks, at which time a request will be forwarded to the contracting agency for coverage of costs to be incurred in provision of the special antenna system required. Mention has already been made to Ozzie and to Kelly that it would be most desirable to have the C-47 airplane made available for flight tests on the complete system.

Conferences will be arranged with technical personnel of the contracting agency to determine the need for establishment of a second ground base within the United States to facilitate navigation system tests. It is probable, but not necessary, that a second base be established in the vicinity of Washington.

Full scale tests of the C and N system will necessitate flying the test airplane to distances as great as 3000 to 4000 miles from Los Angeles. Some of the flights should be made in an essentially easterly direction from this city; it would be desirable to plan others along more nearly north-south paths. Aside from problems incident to flying over Canadian territory, the presence of the "auroral" zone which extends northward from southern Canada serves to limit somewhat the usefulness of data which could be gathered on flights directed principally in a northerly sense. From an operational point of view, it is fortunate that the auroral zone does not extend as far southward in the eastern hemisphere as it does in the western; consequently limitations on communication and navigation range imposed by auroral signal absorption will be far less pronounced under operational conditions than under test conditions.

Preliminary planning is under way for a training program to acquaint personnel of the contracting agency with the theory, structure, installation and maintenance of System No. 2 equipment. Information concerning the training program will be submitted for approval at an early date.